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Recent Advances and Applications in Cryogenic Propellant Densification Technology

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Abstract

This purpose of this paper is to review several historical cryogenic test programs that were conducted at the NASA Glenn Research Center (GRC), Cleveland, Ohio over the past fifty years. More recently these technology programs were intended to study new and improved denser forms of liquid hydrogen (LH2) and liquid oxygen (LO2) cryogenic rocket fuels. Of particular interest are subcooled cryogenic propellants. This is due to the fact that they have a significantly higher density (e.g. triple-point hydrogen, slush etc.), a lower vapor pressure and improved cooling capacity over the normal boiling point cryogen. This paper, which is intended to be a historical technology over-view, will trace the past and recent development and testing of small and large-scale propellant densification production systems. Densifier units in the current GRC fuels program, were designed and are capable of processing subcooled LH2 and LO2 propellant at the X33 Reusable Launch Vehicle (RLV) scale. One final objective of this technical briefing is to discuss some of the potential benefits and application which propellant densification technology may offer the industrial cryogenics production and end-user community. Density enhancements to cryogenic propellants (LH2, LO2, CH4) in rocket propulsion and aerospace application have provided the opportunity to either increase performance of existing launch vehicles or to reduce the overall size, mass and cost of a new vehicle system.

Introduction

The NASA Glenn Research Center (GRC) has led the nations' effort in the development of production and handling technology of densified cryogenic propellant systems for aerospace and launch vehicle application. The technology of sub-cooling cryogenic propellants below their normal boiling point and thereby making the fluid denser is one of the key process technologies necessary to meet the challenge of single-stage-to-orbit (SSTO) and reusable launch vehicles (RLV). Densified propellants are critical to lowering payload to orbit costs because they enable more cryogenic propellant to be packed into a given unit volume, thereby improving the performance of a launch vehicle by reducing its overall size and weight. Density improvements of 8% for LH2 and 10% for LO2 are expected to reduce the gross lift-off weight of a launch vehicle system by up to 20 percent.

Glenn research engineers are currently working on providing methods and critical test data for the continuous large-scale production of densified liquid hydrogen and densified liquid oxygen. Five years ago, the prototype equipment and process technology for continuously subcooling LH2 propellant below the normal boiling point was initiated at GRC. Recent analysis and test results have led the aerospace community to accept the notion that high-density propellants are an enabling technology for a viable RLV system. Going further back in time, the batch production and testing of slush hydrogen (SLH2), a 50 wt% mixture of liquid and solid hydrogen, was performed at the GRC during the early 1990's to support the National Aerospace Plane (NASP) program. Large 800 gallon batch quantities of 50 wt% SLH2 were produced using a freeze-thaw evaporative cooling technique. The very early history of cryogenics research at the GRC ultimately began with the space race initiative. The push to develop manned space technologies started in the 1950's when LH2 was the rocket propellant of choice to fuel the upper stage of several classes of launch vehicles.

This paper will qualitatively and briefly describe several past and recent programs initiated at the Glenn Research Center involving cryogenic fuels and propellant densification. Densified propellant research and testing conducted and sponsored by the National Aeronautics and Space Administration (NASA) to date has principally involved cryogenic fluids most commonly used in the aerospace community. These include liquid nitrogen, oxygen, hydrogen and liquid helium. A basic technological overview of the NASP slush hydrogen program including production equipment and test results will be presented. A descriptive summary of the cryogenic processing hardware used in each propellant densification system approach, along with a summary of test results are reported. Finally, thoughts on other practical approaches to densifying propellants and potential commercially viable methods for the production and end-use application of densified-subcooled cryogenic fluids will be described. Densifier refrigeration concepts extending over the temperature range from normal boiling point liquid methane (201 ºR) down to liquid helium (3.9 ºR λ) are of more interest to chemical engineers working in the cryogenics industry and thus from an applications viewpoint will be briefly reflected upon.

Cryogenic Research at LeRC from 1945 to 1988[1]

The history of cryogenic research at the NASA Lewis Research Center (LeRC), which was recently renamed in 1999 to the "NASA Glenn Research Center at Lewis Field," began in the mid-1940's. At that time when the agency was referred to as the National Advisory Committee for Aeronautics (NACA), researchers at the Lewis Laboratory were studying alternate potential rocket fuels. The rocket research group, established at Lewis in 1945, knew then that a liquid hydrogen/liquid oxygen powered vehicle could provide a 40% increase in payload capability over other propellant combinations.

In the early 1950s', a Lewis team began to develop pioneering techniques in the handling of liquid hydrogen[2] and liquid oxygen and had operated small chemical rocket engines with LH2 as a fuel. By 1954, the rocket research group at the Lewis Laboratory had developed the nations' first regeneratively cooled liquid hydrogen-liquid fluorine rocket with 5000 pounds of thrust. Then for the first time in aviation history, a test with a single LH2 fueled modified Curtis Wright J-65 jet engine on a B-57B bomber was conducted in 1955. The test nicknamed "Project Bee", had not only led to a successful flight demonstration over nearby Lake Erie but established early procedures for the storage, handling and transfer of liquid hydrogen propellant.

The completion of the Rocket Engine Test Facility (RETF) in 1957 provided the Lewis Laboratory with a significant LH2-LO2 hot-fire experimental capability. This facility provided test conditions up to 20,000 pounds of thrust at either sea-level or vacuum exhaust. Much of the Pratt & Whitney's RL10 expander cycle LH2-LO2 rocket engine development tests were conducted at the RETF. With the start of the Saturn program, the decision to fuel the upper stage of the Saturn V with liquid hydrogen versus kerosene fuel was controversial within the NACA agency. In December of 1959, Dr. Abe Silverstein, a senior NASA engineer had convinced the Von-Braun supporters of conventional fuels that the upper stage should use liquid hydrogen to power men to the moon.

In the 1960s, under the leadership of LeRC Center Director Dr. Abe Silverstein, the basic research into LH2 technology was truly a milestone in modern cryogenics history. He led the investigation and development of liquid hydrogen as the principal fuel for the Centaur upper stage. In 1962, LeRC was named the lead center for the Centaur program. Classical experimental heat transfer studies[4-5] with liquid hydrogen were carried out by a LeRC group working in the Cryogenic Heat Transfer Section. Between 1961 and 1966, their testing had proven the feasibility of using LH2 as an engine coolant.

As a pre-validation test of the Apollo program Saturn V application, the LH2/LO2 powered Centuar upper stage would ride on top of an Atlas rocket. This mission sent a space probe named Surveyor to land and photograph the moons lunar surface in May 1966. The highlight of the Apollo era occurred in 1969 when Apollo 11 astronauts first set foot onto the surface of the moon. As the race to the moon and the Apollo program[3] ended, between 1970 and the mid-1980s, much of the cryogenic research and testing at LeRC focused on cryogenic storage, supply and transfer in support of deep-space exploration programs. Research and testing involved LH2 tank thermodynamic studies, tank pressurization testing, no-vent cryogenic fill, tank thermal control with Multi-Layer Insulation (MLI) materials and in-space propellant technology management work. Meanwhile, the development of the LH2-LO2 fueled Space Shuttle, a reusable space transport plane, had other NASA centers coming to the LeRC for fundamental cryogenic research in support of pumps, seals, injectors and combustion chamber heat transfer technology. These and other significant events, tracing the history of cryogenic propellant research and testing that has occurred at the LeRC between 1945 to present is summarized in Table 1.0.

Table 1.0: Historical events in cryogenic research and testing at LeRC from 1945 to present.

Year	***Cryogenic Research Event / Accomplishment at LeRC***
1945	Rocket Research Group established to study fuels and LH2
1953	Hydrogen liquifier installation completed
1954	Regeneratively cooled LH2-LF2 rocket developed (5000 lb_f thrust)
1955	LH2 fueled modified J-65 jet engine flight test of B-57B bomber
1957	Rocket Engine Test Facility completed - 20,000 lb_f LH2-LO2 test capability at sea-level or vacuum exhaust condition
1958	NACA becomes new NASA organization. Lewis Laboratory renamed to the NASA Lewis Research Center
1959	NASA selects LH2 to fuel Upper Stage of Saturn V launch vehicle
1962	LeRC named lead center for Centaur program – Pratt & Whitney RL10 H-O engine development commences at RETF
1961 - 1966	Classical LH2 heat transfer studies prove LH2 as an engine coolant
1966	LH2/LO2 powered Atlas-Centuar upper stage sends Surveyor probe to land and photograph moons lunar surface.
1969	Apollo 11 astronauts land on the Moon powered w/H-O upper stage
1970 - 1985	LeRC cryogenic research and testing focuses on cryogen storage, supply and transfer to support space exploration programs
1988 - 1994	NASP Slush Hydrogen Technology Program - large scale production, transfer and in-tank thermodynamics testing with SLH2
1995 - 1997	LH2 densification prototype system - 2 lb_m/sec rig testing at K-Site
1996	Hot fire ignition test of RL10B-2 engine with densified LH2
1998	Demonstration of LH2 thermal stratification in a composite prototype flight weight dual-lobe tank conducted at K-Site
1997- Present	Design and test of large scale LO2-LH2 propellant densification units for X-33/RLV flight experiment with high-density propellant

Cryogenic Research at LeRC from 1988 to Present

During the last eleven years, extensive research into the production and handling of densified propellants has been conducted at LeRC. The benefits of densified propellants, LH2 and LO2 to reduced launch vehicle size and increased payload to orbit were well demonstrated during the 1980's. Several programs were initiated to bring this technology from the laboratory to the launch site.

Properties of High Density Cryogenic Propellants[6]

High performance rocket propellants are fuels with special desirable characteristics. These include high energy, high density, good heat capacity for cooling, fast mixing and rapid combustion kinetics. With the exception of the high-density property, LH2 is the only known propellant with all of these advantageous features. When reacted with liquid oxygen, LH2 has the highest energy release per pound of any propellant combination. The energy release of a propellant, notably referred to as specific impulse (I_{SP}) is ~390 seconds for the LH2-LO2 system. The I_{SP} relates thrust $\boldsymbol{F}$ (lb_f) to chamber propellant mass flow rate $\boldsymbol{W_{tc}}$ (lb/sec) and is a useful measure of propellant efficiency in terms of thrust per unit $\boldsymbol{W_{tc}}$.

$$I_{SP} = \frac{F}{W_{tc}}$$

The principle disadvantage of liquid hydrogen however is its' remarkably low density. The density of liquid hydrogen at its normal boiling point is only 4.42 lb_m/ft^3. In contrast to the density of water at 62.4 lb_m/ft^3, hydrogen has the lowest density of any known fluid. When subcooled to the triple point (TP) of 24.8 ºR, LH2 becomes 9% greater in density and provides a 12% increase in cooling capacity compared to the Normal Boiling Point (NBP) condition of 36.4 ºR. Like all cryogenic liquids, as you move further along the LH2 saturation curve (fig 1.0), the vapor pressure decreases as temperature decreases and the fluid density rises. It is this type of fluid behavior that enables one to control propellant density by simply changing the vapor pressure above the cryogenic liquid.

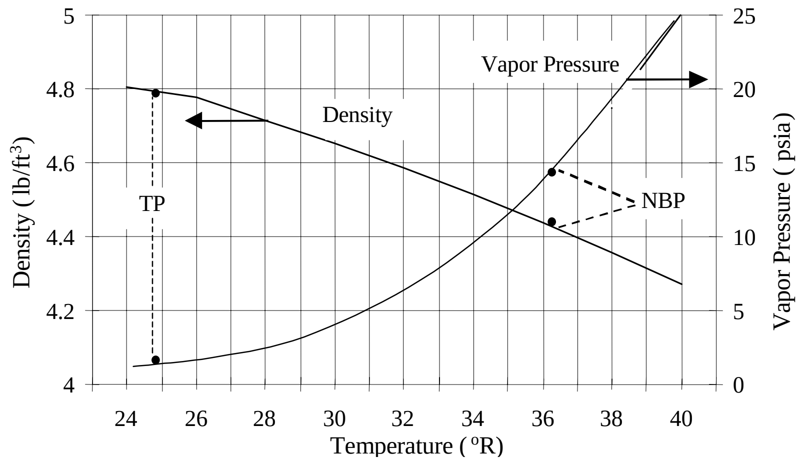

Figure 1.0—Liquid hydrogen density and vapor pressure curves.

Certain physical properties in Table 2.0 demonstrate the effect of subcooling on density for cryogenic methane, para-hydrogen and oxygen at TP and for slush mixtures. A fifty weight percent mixture of SLH2 is 15% denser, and has 18% greater cooling capacity than NBP LH2. Similar density increases are achievable with subcooled liquid methane and triple-point or slush oxygen.

Table 2.0: Density effect and fluid properties for methane, hydrogen and oxygen.

Property	methane	p-hydrogen	oxygen
Molecular Weight (lb_m/lb-mol)	16.042	2.016	32.000
Normal Boiling Point (ºR)	201.0	36.4	162.4
Density @ NBP (lb_m/ft^3)	**26.37**	**4.42**	**70.8**
Triple Point Temperature (ºR)	163.3	24.8	97.8
Triple Point Pressure (psia)	1.70	1.022	0.022
Triple Point Liquid Density (lb_m/ft^3)	**28.20**	**4.81**	**81.6**
Solid Density (lb_m/ft^3)	31.90	5.40	84.9
Heat of Fusion (Btu/lb_m)	26.10	25.05	5.967
Heat of Vaporization (Btu/lb_m)	219.6	191.7	91.63
Slush Density @ 50% solid (lb_m/ft^3)	**30.05**	**5.10**	**83.25**
% Density Increase, NBP-to-Slush	14.0	15.4	17.6

Slush Hydrogen Experimentation[7–9]

In 1988, an extensive program was started at the LeRC, Plum Brook Station, in Sandusky, Ohio to develop large scale slush hydrogen production capabilities in support of the National Aerospace Plane Program (NASP). By 1990, the first slush hydrogen test series began at a modified K-Site Propellant Tank Research Facility. The slush hydrogen production system designed by Air Products included a 1300 gallon SLH2 generator, a mixer, a 10000 scfm vacuum pumping system and extensive instrumentation. An aerial photograph of the K-Site test facility and SLH2 generator equipment tower is shown in figs. 2.0 and 3.0, respectively.

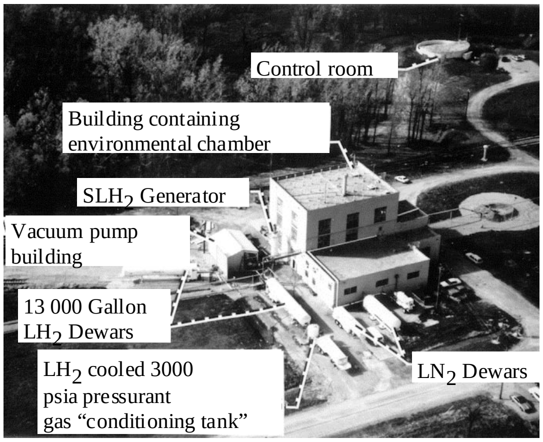

Figure 2.0—NASA Plum Brook K-Site facility.

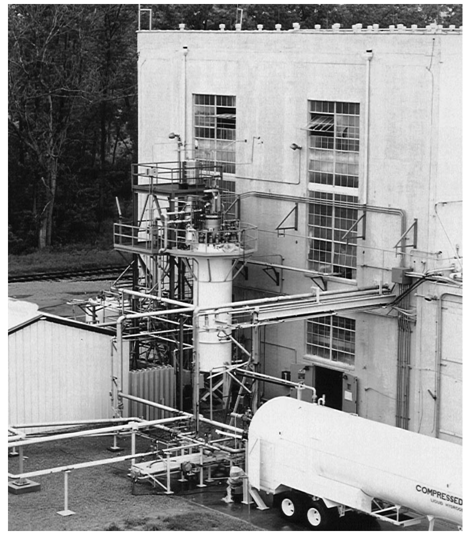

Figure 3.0—K-Site SLH2 production equipment.

Production, fluid transfer and in-tank thermodynamics testing with SLH2 continued through 1994. Over 200,000 gallons of 50 – 60 weight percent solids SLH2 were produced in 800 gallon batch quantities using a freeze-thaw vacuum pumping process. A typical production batch cycle time with this system was two to three hours. The SLH2 data base created by GRC researchers included production, storage, pressurized and pumped transfer, tank pressure control, propellant mixing, condensation of recirculated gH2, thermodynamic response to sloshing, and SLH2 densiometer development. Results of SLH2 flow experiments[10] showed that pressure drop (ΔP) for two-phase slush followed the traditional fluid flow model given by a relation derived from the Darcy-Weisbach equation

$$m = \sqrt{\frac{288\ D\ A^2\ g_c\ \rho\ \Delta P}{f\ L}}$$

where A is the flow area (ft^2); D is pipe diameter (ft); f is friction factor; g_c is 32.2 ft/sec^2; L is flow length (ft); m is mass flow rate (lb/sec); ΔP is pressure drop (psi); and ρ is fluid density (lb/ft^3).

Densification Technology Description

Propellant densification refers to processing techniques designed to increase the fluids’ mass per unit volume (ρ_f). The GRC concept of the propellant conditioning unit shown in fig. 4.0 is based on a thermodynamic vent approach. The system consists of a cryogenic heat exchanger, a compressor and a recirculating pump. Depending on the application, a single tank can be used to densify the fluid by recirculation in a closed-loop through the refrigeration unit. A two tank densifier configuration would involve flow of NBP from a supply dewar through the refrigeration unit then to a densified product receiver dewar.

In this case, propellant densification is achieved by flowing normal boiling point liquid through a heat exchanger. To generate the subcooled densified propellant, the heat exchanger bath is filled with a coolant. For densifying LH2 to an outlet temperature of 27 ^{o}R, the cold side of the heat exchanger is a bath of liquid hydrogen saturated at a sub-atmospheric pressure of 1.1 psia. This produces a “heat sink” of 25.4 ^{o}R. Densification of LO2 to a temperature of 120 ^{o}R employs a bath of saturated liquid nitrogen at 2.5 psia and 117 ^{o}R. Thus, by using a bank of compressors to decrease the pressure below atmospheric, the liquid bath is forced to boil down to a lower temperature creating a heat sink relative to the propellant flowing through the “warm side” of the heat exchanger. The compressor is designed to reject the low-pressure boil-off gas to an atmospheric pressure vent system. In some cases, the refrigeration enthalpy capacity of the vented gas may be used either to cool some secondary stream or the gas itself can be recovered for reuse as a purge, a fuel, etc.

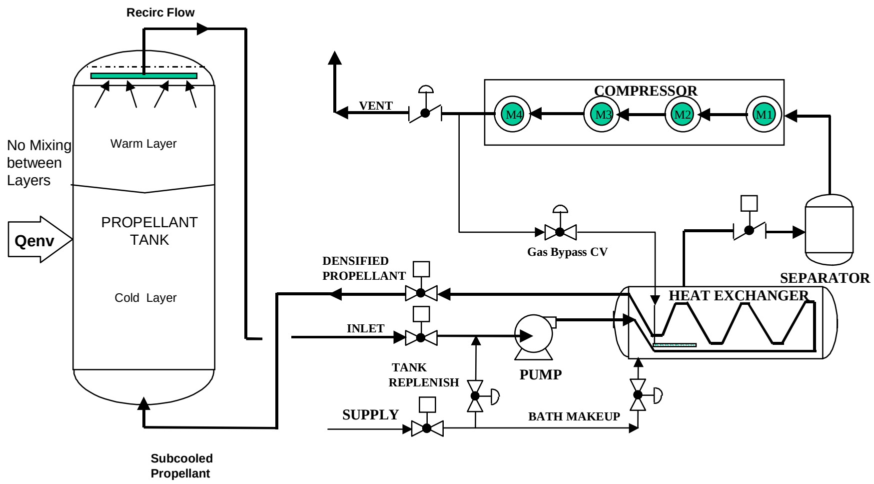

Figure 4.0—Schematic diagram of propellant densification (refrigeration) unit.

Densified Propellant Testing

In 1995, with the reusable launch vehicle (RLV) program emerging, production technology work once again began at GRC[11]. The effort was driven by the significant vehicle mass reduction offered to RLV with subcooled LO2-LH2. By December of 1996, a 2.0 lb_m/sec LH2 prototype densification system (fig. 5.0) was successfully tested at K-Site. The unit first underwent check-out trials by densifying LN2 to 120 ^oR. Following this was a series of performance tests[12] that proved the hardware and design concept as LH2 was subcooled down to 30 ^oR. One year later, under a cooperative agreement with Lockheed Martin Michoud Space Systems, a repeat test series was completed with the LH2 prototype densifier to further expand the performance data-base. In parallel with that effort, GRC engineers had the opportunity to conduct a hot-fire ignition test[13] using near-triple point LH2 with a Pratt & Whitney RL10B-2 engine. This short duration test, performed at NASA Plum Brook Station in 1996, successfully demonstrated that the engine, shown in fig. 6.0, could be ignited outside of its' original "ignition design window" using subcooled LH2.

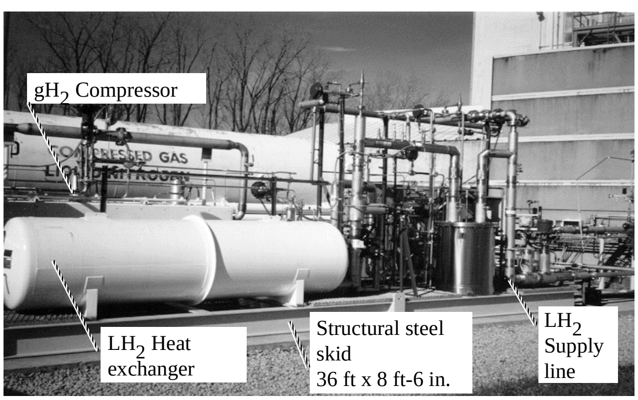

Figure 5.0—Skid mounted 2 lb/sec LH_2 propellant densification assembly.

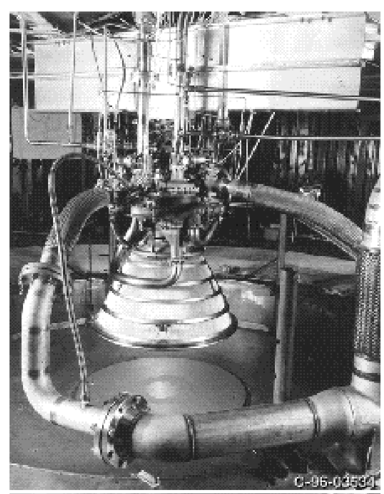

Figure 6.0—RL10B-2 rocket engine mounted in the B-2 facility for densified LH_2 ignition test.

The current densification program[14-15] that started at the GRC in 1997, involves the development and test of two large scale LO2 and LH2 propellant densification production units. These systems were designed to support a future X-33 flight experiment with high-density propellants on-board. Each densifier is configured with a high-efficiency, sub-atmospheric boiling bath heat exchanger to cool the working fluid. A near triple-point LH2 boiling bath is used to condition and subcool hydrogen product down to 27 ^{o}R, and a nitrogen boiling bath at 117 ^{o}R provides the heat sink to cool liquid oxygen to 120 ^{o}R. Multistage high-speed centrifugal compressors operating at cryogenic inlet conditions maintain each heat exchanger bath and vapor pressure below one atmosphere. The LO2 propellant densification unit shown in fig. 7.0 has a processing capacity of 30 lb_m/sec (190 gpm). The LH2 unit is designed to produce 8 lb_m/sec (820 gpm) of high-density LH2. Both of these large cryogenic densification systems are enhanced 4:1 scaled-up versions of the 2 lb_m/sec LH2 densifier that was previously operated in 1996.

After all fabrication and check-out work is completed sometime in the spring of 2000, each densification unit will be integrated with the South-Forty test area located at the GRC. This is where LO2 and LH2 densifier performance tests will be performed with another large propellant tank designated the Structural Test Article (STA). The STA liquid oxygen tank is a full-scale, flight-weight, prototype aluminum tank designed for X-33. The STA has a capacity of 20,000 gallons of LO2. This years' planned loading and recirculation testing with the STA will provide the data necessary for full-scale implementation of propellant densification technology for the flight experiment, RLV or potential Space Shuttle Upgrades.

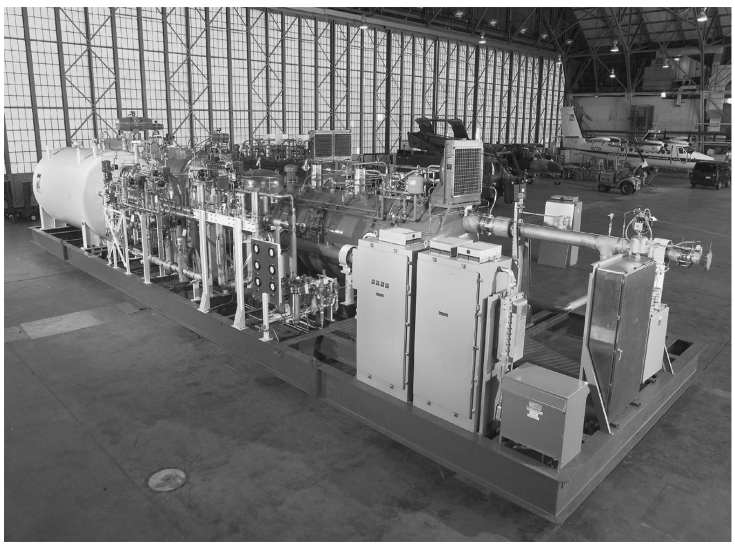

Figure 7.0—Assembly of the X-33 sized liquid oxygen propellant densification unit designed and fabricated by the NASA Glenn Research Center.

Densification Technology in Commercial Application

Production and use of densified propellants have several potential non-aerospace applications. These applications extend from laboratory research to low temperature industrial gas processing.

• Subcooling cryogenic fluids below their normal boiling point (NBP) can provide researchers in low-temperature physics with "intermediate constant-temperature-bath" cold sinks. Temperatures in-between the NBP and TP of cryogenic fluids typically used in laboratories is shown in fig. 8.0. By controlling the heat exchanger pressure, the Thermodynamic Vent System (TVS) concept can be applied to variable temperature refrigeration. Temperatures differentials of these particular cryogenic fluids span from liquid methane at 37.7 ºR, LO2 at 64.6 ºR, LN2 at 25.5 ºR, LH2 at 11.6 ºR, all the way down to a liquid helium ΔT of 3.7 ºR.

• The development of the GRC densification system cryogenic compressor hardware has alternate technology uses of its own. In a gas compression cycle, the power requirement of the compressor is directly proportional to inlet gas temperature. For the same mass flow and compression ratio, the power needed to compress saturated gN2 vapor at 140 ºR is approximately four times less than the power required at ambient inlet temperature conditions. This energy savings potential could be extended to typical compressed air plants and distribution systems. The application may find use in a manufacturing facility which utilizes both LN2 and also requires a source of relatively low temperature refrigeration.

• Densification technology may even be applied to liquid air separation plants. The same type of densification system could be used to increase the fluid density of the product cryogenic liquids. Other subtle benefits include: (a) reduced boil-off loss of cryogens in storage resulting from the lower vapor pressure, and (b) increased delivery loads of cryogenic fluids to a customers site given a fixed capacity tanker-trailer to transport the liquids. Another benefit resulting from the higher density fluid can lead to reduced product storage cost of CH4, LN2 and LO2 dewars. Figure 9.0 compares cost estimates of commercial storage dewars for NBP LN2 from 6 kgal to 50 kgal sizes. The three curves shown below the NBP LN2 line represents the same storage capacity based on equal mass of triple-point fluid as well as the lower associated capital cost for the smaller volume dewar.

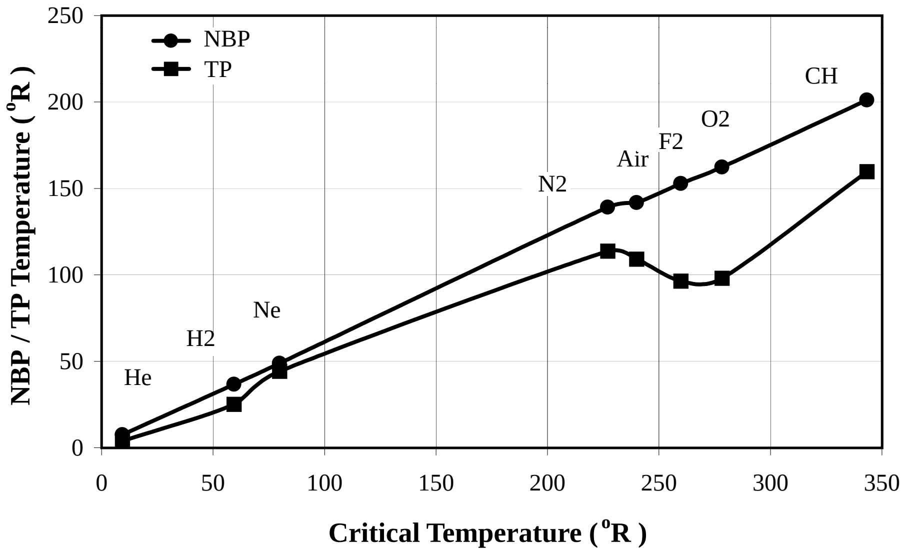

Figure 8.0—Cryogenic fluid temperature differential between normal boiling point and triple point.

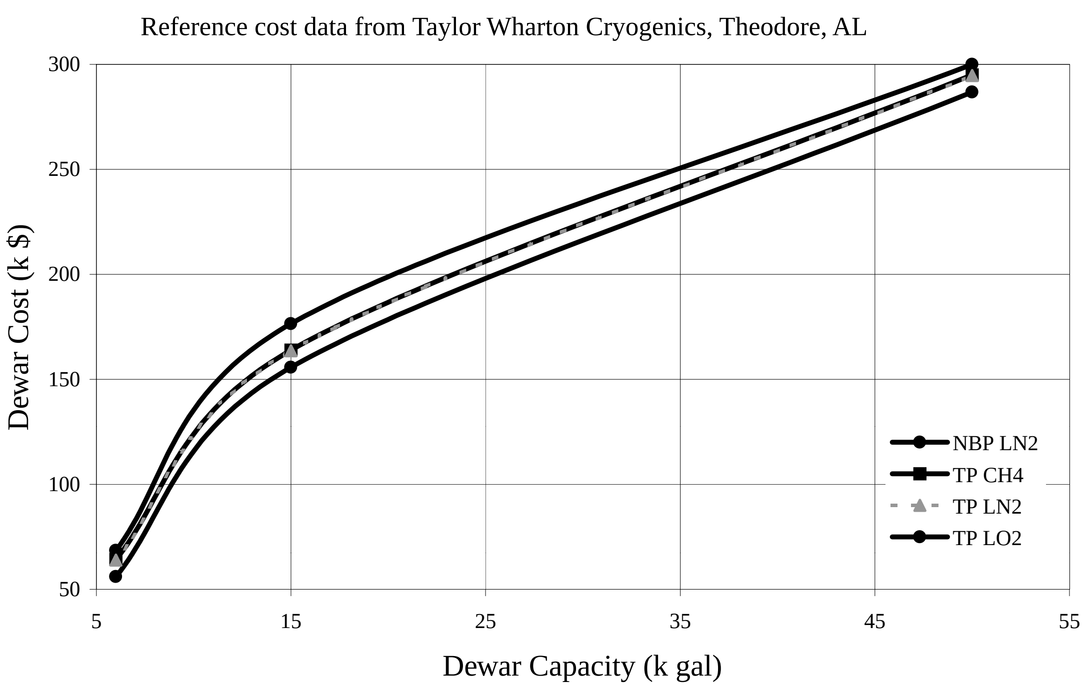

Figure 9.0—Cryogenic fluid storage dewar costs for NBP LN2 in comparison to densified triple-point LN2, CH4 and LO2.

Concluding Remarks

The NASA GRC has a traditionally unique history in the field of cryogenics research and testing. Over the past ten years, subcritical cryogenic propellants research at the GRC has focused on developing production techniques, demonstrating handling capabilities, and defining performance characteristics of high-density cryogenic propellants. Recent emphasis has been placed on the development of predictive analytical models[16] that describe the thermodynamic state and fluid dynamic environment for the propulsion system during loading and take-off. Experimental programs have been designed with propellant quantities scalable for full-size propulsion systems. Research areas have included densified liquid hydrogen and oxygen, slush hydrogen, metallized gelled Earth storables (NTO, MMH, RP-1), gelled liquid hydrogen[17-18], atomic hydrogen[19] and high-energy density propellants. Interest continues to grow in the aerospace community with the use of high-density propellants. Just recently, Aerojet[20] ran NK-33 engine tests with LO2 subcooled to 145 ^{o}R and RP-1 hydrocarbon rocket fuel cooled down to -37 ^{o}F. These propellants were processed by densification hardware similar to the GRC units. Additionally, with the advancement of "high-temperature" superconductors approaching LN2 temperature, the commercial use of densified cryogens is more than likely to expand for cooling of conductors.

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13. ABSTRACT ***(Maximum 200 words)***
This purpose of this paper is to review several historical cryogenic test programs that were conducted at the NASA Glenn Research Center (GRC), Cleveland, Ohio over the past fifty years. More recently these technology programs were intended to study new and improved denser forms of liquid hydrogen (LH2) and liquid oxygen (LO2) cryogenic rocket fuels. Of particular interest are subcooled cryogenic propellants. This is due to the fact that they have a significantly higher density (eg. triple-point hydrogen, slush etc.), a lower vapor pressure and improved cooling capacity over the normal boiling point cryogen. This paper, which is intended to be a historical technology overview, will trace the past and recent development and testing of small and large-scale propellant densification production systems. Densifier units in the current GRC fuels program, were designed and are capable of processing subcooled LH2 and LO2 propellant at the X33 Reusable Launch Vehicle (RLV) scale. One final objective of this technical briefing is to discuss some of the potential benefits and application which propellant densification technology may offer the industrial cryogenics production and end-user community. Density enhancements to cryogenic propellants (LH2, LO2, CH4) in rocket propulsion and aerospace application have provided the opportunity to either increase performance of existing launch vehicles or to reduce the overall size, mass and cost of a new vehicle system.

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